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CONSTRUCTION AND DESIGN OF FOUNDATION ELEMENTS

The present invention relates to a foundation element and a method of designing and forming the same. In particular, the present invention relates to a foundation element which is designed by consideration of a number of parameters including the contribution of ground material to the overall bearing capacity of the element.

Foundation elements such as piles made from concrete or grout are used in the construction industry to provide support for buildings or other large structures. They may be formed in a number of ways such as installing a pre-formed element vertically in the ground. Alternatively, cast-in-situ methods are commonly used by the piling industry, which involve driving or boring a piling tool to a certain depth, and then withdrawing the tool from the ground while concurrently or subsequently pouring or pumping concrete or grout to the tip of the tool so as to fill the underground void left by the tool.

The calculation of load bearing capacity of a foundation support structure plays a vital role in any building operation. Not only is it important to ensure that the structural load can be fully supported by the foundations, but the overall cost of the foundation structure must also be considered to ensure that the volume of concrete or grout required, and the labour involved in its construction, is optimised.

Within the piling industry, regard is given to a number of established principals when carrying out the design and calculation of the load-bearing capacity of an underground foundation structure. Consequently, piling

operators and contractors, within the UK and overseas, tend to follow a number of working "rules" when trying to optimise parameters such as concrete type and element dimensions.

Therefore, the dimensions, concrete type and consequently the strength of the piles are selected in accordance with the weight of the above ground structure and it is typical to design the pile shaft dimensions according to the allowable stress which will be exerted on the resultant pile for the chosen concrete type. Furthermore, it has been found that the friction experienced between a foundation element and the surrounding ground material, known as "skin friction", effectively carries a proportion of the structural load, thereby reducing the stresses in the concrete section. Thus, the distance around the perimeter of the resultant element is related to the amount of friction experienced between the element and the concrete. The diameter of a cylindrical pile for example will therefore have a direct consequence on the stress exerted on the concrete.

In the use of cylindrical piles, a relative increase in cross sectional area causes the stresses experienced by the concrete column to decrease. Since in the piling industry large loads frequently have to be supported, large diameter piles are often adopted to transfer the load to the soil. However, due to the large volumes of concrete required, large diameter piles are generally inefficient in terms of concrete stress and can be time consuming to install.

The inventors consider that two important and unexpected factors have so far been overlooked by the piling industry during the construction and design of

foundation elements having an adequate load bearing capacity.

During the installation process of a foundation element such as, for example, a conventional bored pile, the soil within the vicinity of the pile becomes disturbed and, as a result, adhesion between the pile and the soil becomes lower than would correspond to an undisturbed region of soil, with soil to soil contact. As a result, the soil surrounding the pile will have a lower frictional bearing capacity than undisturbed soil. This effect has meant that the full potential contribution of the soil to the bearing capacity of a foundation structure has not been taken into account.

The strength of a series or group of piles is conventionally taken to be a variable fraction of the sum of the individual piles, depending on the pile spacing. The reduction applied might typically reduce potential capacity by 20%. The piling industry therefore considers that the group effect of a plurality of piles is that the group capacity is less than the sum of the individual piles. Indeed, present testing regimes for determining the bearing capacity of a pile or other foundation element involve the application of test axial forces to the top of a single pile to measure the settlement of that pile. To date, there has been virtually no testing of groups of piles.

A consequential working rule adopted by the piling industry is to maintain a minimum separation between adjacent piles. This general rule for installing a series of piles is that the spacing between piles is kept at about 3 times the diameter of the pile and should be determined with regard to the nature of the ground, the behaviour of the piles as a group and the

overall cost of the foundation. Since a significant proportion of the load is carried by a pile in the skin friction along the surface of the pile, it is important that the adjacent pile surfaces are not damaged during the installation of other piles. It is uncommon to install piles in closer proximity than the recommended limits. Although piles may occasionally be installed closer together because of space restrictions or when used in retaining wall structures, it is common practice to follow the standard codes set by the piling industry.

The applicants have found, contrary to common piling practice, that by installing a plurality of piles in the ground in close proximity, a composite pile-soil element is formed in which the soil between the piles becomes integral with and moves together with the piles, thereby contributing to the overall load bearing capacity of the element. Furthermore, any undisturbed soil between the external concrete elements of a composite group will further contribute to the strength of the foundation element.

Another factor, that has until now not been fully considered, is the shape and constitution of the interface between a foundation element and the surrounding ground material. Consider, for example, a ribbed pile such as that illustrated in Figure 2. The skin friction of such an element is conventionally calculated on the basis of the adhesion between the concrete along the perimeter of the element and the surrounding soil. However, the applicants have found that there actually exists a volume of relatively undisturbed soil within a curved failure plane between adjacent ribs. This contained soil will not only contribute to the load bearing capacity of the element,

but the adhesion and thus the skin friction between the contained soil and the surrounding soil is actually greater than the adhesion between the soil/concrete interface. By consideration of the contribution that this relatively undisturbed soil will have to the overall load bearing capacity of the pile, a more realistic analysis of the overall load bearing capacity can be achieved.

According to one aspect of the present invention there is provided a method of designing a foundation element, wherein the foundation element comprises a volume of concrete and a volume of ground material, the method comprising the steps of:

i) determining the total load bearing capacity required by the foundation element;

ii) determining the parameters of the foundation element by consideration of the contribution of the volume of ground material to the overall load bearing capacity of the foundation element.

According to a further aspect of the present invention, there is provided a method of analysing the load bearing capacity of a foundation element, wherein the foundation element comprises concrete and ground material, the method comprising the steps of:

i) determining the volume and strength of the concrete; and

ii) determining the volume and shear strength of ground material which contributes to the overall bearing capacity of the foundation element.

In optimising the design of the foundation, and in analysing the bearing capacity of a foundation element in accordance with embodiments of the present invention, further consideration is preferably given

to: the skin friction between the perimeter of the foundation element and the surrounding ground material; and/or the mean shear strength of the predetermined volume of concrete in relation to the contacting ground taking into account the radius of the curved failure plane which develops between discrete concrete sections at the periphery of the element.
The predetermined volume of concrete may advantageously comprise a plurality of discrete concrete sections separated by the predetermined volume of ground material or, alternatively, a monolithic section with a plurality of peripheral concrete sections.

By means of a computer program or any other calculation technique, the load bearing capacity of a given foundation element can be found and indeed the design of a foundation element can be optimised for given constraints such as concrete strength, space available and structural load. Importantly, the volume of concrete required to make a single foundation element can be optimised by consideration of the composite contribution of soil to the load bearing capacity and the adhesion perimeter between the element and the surrounding soil. When a plurality of discrete concrete sections, such as piles, are installed, the conventional rules about spacing can be dispensed with, and it is only necessary to ensure that the piles can properly be formed without damage.

The foundation element may comprise a plurality of individual piles which are installed in the ground in close proximity in a predetermined arrangement. The contribution of the relatively undisturbed soil between adjacent piles means that the group of piles can be considered as acting as a single element such as a large diameter pile. However, due to load bearing

capacity of the soil and the adhesion between contributing soil and surrounding soil, there is a considerable reduction in concrete required to achieve a given load bearing capacity.

According to a third aspect of the present invention, there is provided a composite foundation element, comprising a volume of concrete and a volume of ground material, wherein the parameters of the foundation element have been determined by consideration of the contribution of the volume of ground material to the overall load bearing capacity of the foundation element.

It is envisaged that the spacing between the concrete sections of the composite element may be 2 to 2.5 times the concrete section diameter or less. From a practical point of view, the separation between the concrete sections must be sufficient to ensure that the piles are not damaged during the installation process.

A group of piles behaving in composite action will develop high cross-sectional stresses with generally shorter lengths than more conventional piles sizes. As a result of this they are efficient and economical load bearing units. It is therefore envisaged that foundation elements such as this, embodying the present invention, can be used to replace large diameter bored piles. The use of a closely spaced group of "mini piles" has been disregarded by the piling industry due to the recommended spacings between piles and also due to the well known assumption that the bearing capacity of a group of piles has been taken to be a fraction of the sum of the individual piles.

Furthermore, the applicants have found that there are a

number of additional advantages to be obtained by installing a composite foundation element of the present invention. Due to the relatively small dimensions envisaged for the constituent piles or concrete sections, the equipment necessary for the formation of the concrete sections is relatively small and light and provides the opportunity for heavily loaded composite piles to be formed in limited headroom and areas of confined or difficult access. Furthermore, the difficulties of inspection and cleaning which are involved in the process of large diameter piling are greatly reduced. Likewise, the volumes of spoil removed and concrete supplied are also reduced which has both environmental and economic benefits. It is also envisaged that large under-reamed piles may be replaced by a composite foundation element of the present invention, thereby eliminating the risk of under-ream collapse and reducing site hazards which are safety matters associated with large diameter under-reamed pile construction.

In clay soils it is conventional practice to measure the shear strength of the soil using undrained triaxial tests. These are plotted against sample depth and a strength/depth line may be plotted. Shaft friction is calculated for a given concrete section by taking the mean shear strength from the strength/depth line and multiplying it by an adhesion reduction factor. Where for example clay shears against clay, then the common adhesion reduction factor may be dispensed with.

It is clear that the perimeter of such a composite pile is not cylindrical, neither is it defined by drawing tangents between each concrete section. It is however legitimate to make the assumption of clay shearing in a circular arc between each two concrete sections

provided that the radius of the arc is given freedom to range and find the minimum solution taking adhesion and cohesion surfaces into account concurrently with a base area which is bounded by the same surfaces.

Such analysis yields a minimum load for the composite foundation element, which may then be compared to the equivalent non-composite foundation element, such as a large diameter pile and the equivalent number of isolated elemental piles.

Furthermore, it is important to ensure that the settlement of the composite pile is acceptable for the applied structural load. This can be determined by consideration of: the single pile element settlement relative to the composite foundation unit including the elastic shortening; and/or adding the composite unit settlement calculated on the basis of a single pile-like element of equivalent calculated dimensions.

In order to prevent independent concrete sections from slipping through the element, it is preferable for each section to carry a load which is approximately equal to the load applied to the composite element divided by the number of piles.

For a better understanding of the present invention, and to show how the same may be carried into effect, reference will now be made by way of example to the accompanying drawings in which:

Figure 1 shows a composite foundation element embodying the present invention having a plurality of discrete concrete sections;

Figure 2 shows a composite foundation element embodying

the present invention, having a ribbed monolithic concrete section; and

Figure 3 shows a composite foundation element embodying the present invention, having a ribbed monolithic concrete section.

The composite foundation element as shown in figure 1 comprises a plurality of discrete concrete sections in the form of cylindrical piles 1 and a volume of ground material 2. Each pile has a diameter Dp, wherein the separation between the centres of adjacent piles is defined by S. There exists a predetermined volume of compacted or undisturbed soil 2 disposed between the piles and the composite foundation element is taken to comprise the pile group which defines a rectangular perimeter and the ground material which falls within that perimeter. The pile group is one with M x N piles and the parameters needed for the analysis/design/construction of an optimum foundation element are:

M = number of piles in one direction (row)
N = number of piles in the direction at right angles (column)
S = spacing of piles centre to centre (square) (m)
R = radius of curved failure plane between piles (m)
Dp= pile diameter (m)
L = length of pile in clay (m)
Cu= mean shear strength along pile shaft (kN/sq.m)
Cub= Shear strength below pile base (kN/sq.m)
alpha = adhesion reduction factor (pile/clay)

The friction around the group perimeter is calculated on the basis that adhesion on a pile surface is alpha x

Cu, but where clay shears against clay it is simply Cu. The clay is assumed to shear on a circular arc between piles of radius R.

In order to illustrate the present invention and by way of example only, two calculations will now be given for two values of S, to show the effect on bearing capacity, both end and frictional, as R is allowed to vary so the peripheral lengths of clay in contact with clay and with concrete change.

Calculation 1

With reference to figure 1, the spacing S of piles 1 is firstly chosen to be 0.4 metres, or 2 times the pile diameter.

Number of piles in M row:	3
Number of piles in N row:	3
Spacing S (metres):	.4
Pile diameter Dp (metres):	.2
Pile length in clay L (metres):	15
Cu average along friction length:	150
Cu at base level (kN/sq.m):	200
Adhesion factor - alpha:	.6

By way of comparison, and to illustrate the contribution of the soil to the total load bearing capacity of a foundation element embodying the present invention, the frictional capacity and the end capacity of each of the piles is multiplied by the total number of piles to give the total capacity of the piles alone:

MN x frictional capacity of each elemental pile = 7634.07

MN x end capacity of each elemental pile = 508.94

MN x total = **8143.01**

It should be appreciated that the formulae used for calculating the frictional capacity and the end capacity are readily known by those skilled in the art.

The following analysis is done in accordance with embodiments of the present invention to show the contribution of the soil 2 to the frictional capacity and the end capacity of the foundation element as a whole. In order to illustrate the effect that consideration of the curved failure plane will have on the capacity calculations, R is allowed to vary between 0.12 m and 0.37 m:

Radius R	friction capacity	Gp end capacity	Gp total capacity	Perimeter dist. (m)	Area sq.m
0.12	8242.54	1400.21	**9642.74**	4.64	0.78
0.17	7755.18	1503.91	**9259.08**	4.23	0.84
0.22	7653.56	1554.65	**9208.21**	4.08	0.86
0.27	7632.65	1587.80	**9220.45**	4.01	0.88
0.32	7637.85	1611.82	**9249.67**	3.96	0.90
0.37	7652.46	1630.26	**9282.72**	3.93	0.91

By way of comparison only, the following calculation has been done on the basis that the foundation element comprises a rectangular block with straight line sides and that the friction is alpha x Cu all around the group:

Friction	Base	Total Load	Perimeter	Base area
5168.23	1784.55	**6952.78**	3.83	0.99

<u>Calculation 2</u>

With reference to figure 1, the spacing S of piles 1 is firstly chosen to be 0.35 metres, or 1.75 times the pile diameter.

Number of piles in M row:	3
Number of piles in N row:	3
Spacing S (metres):	.35
Pile diameter Dp (metres):	.2
Pile length in clay L (metres):	15
Cu average along friction length:	150
Cu at base level (kN/sq.m):	200
Adhesion factor - alpha:	.6

By way of comparison, and to illustrate the contribution of the soil to the total load bearing capacity of a foundation element embodying the present invention, the frictional capacity and the end capacity of each of the piles is multiplied by the total number of piles to give the total capacity of the piles alone:

MN x frictional capacity of each elemental pile = 7634.07

MN x end capacity of each elemental pile = 508.94

MN x total = **8143.01**

The following analysis is done in accordance with embodiments of the present invention to show the contribution of the soil 2 to the frictional capacity and the end capacity of the foundation element as a whole. In order to illustrate the effect that consideration of the curved failure plane will have on the capacity calculations, R is allowed to vary between 0.09 m and 0.34 m:

Radius R	friction capacity	Gp end capacity	Gp total capacity	Perimeter dist.(m)	Area sq.m

0.09	7170.41	1157.04	**8327.46**	4.19	0.64
0.14	6731.37	1239.48	**7970.85**	3.77	0.69
0.19	6678.60	1277.81	**7956.41**	3.63	0.71
0.24	6687.41	1302.55	**7989.95**	3.57	0.72
0.29	6711.39	1320.33	**8031.72**	3.53	0.73
0.34	6738.38	1333.88	**8072.26**	3.51	0.74

By way of comparison only, the following calculation has been done on the basis that the foundation element comprises a rectangular block with straight line sides and that the friction is alpha x Cu all around the group:

Friction	Base	Total Load	Perimeter	Base area
4628.23	1442.55	6070.78	3.43	0 .80

It is clear from the above calculations that the contribution of the soil and the frictional capacity carried at the soil/soil interface, has a significant effect on the total load bearing capacity of a foundation element. In accordance with embodiments of the present invention, by taking these factors into consideration, an optimum foundation element can be designed.

Turning now to figure 2 which illustrates a second embodiment of the present invention in which the concrete component of the composite element comprises a cylindrical pile 6, having a plurality of concrete ribs or protrusions 7. In order to determine a more realistic calculation of the total load bearing capacity when analysing an existing foundation element, or when optimising the design of an element to be constructed, consideration must also be given to the volume of relatively undisturbed soil 8 which exists

within a curved failure plane between adjacent ribs. This soil will not only contribute to the load bearing capacity of the element, but the adhesion and thus the skin friction at 9 between the relatively undisturbed soil and the surrounding soil, is actually greater than the adhesion between the soil/concrete interface. The skin friction at 10 between the edge of the concrete rib and the surrounding soil must also be considered.

Similarly, Figure 3 shows a diaphragm wall 11 having a plurality of concrete ribs 12. Consideration is given to the volume of soil 13 and the friction between the interface 14 between the soil 13 and the surrounding soil, in addition to the skin friction at 15.

The length of the protruding ribs outside the nominally cylindrical or rectangular central envelope and the number of ribs can be optimised for maximum load bearing capacity according to the ground conditions.

The precise geometry of the ribs need only ensure that they are of an appropriate size to withstand the maximum shear stresses that may be generated on that protruding section.
The orientation of the ribs may be nominally parallel to the axis of the central element or, in the case of the cylindrical form, may be allowed to rotate around the central axis according to depth.

The method of formation of these ribs is influenced by the method of installation of the central core of the element. In the case of replacement piles, a specific tool can be inserted into the bore, which when at full depth deploys cutters against the bore walls which form the rib shaped protrusions in one operation as the tool

is extracted. The tool can be predisposed of a suitable spoil catching bucket.